ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2017, Vol. 53, No. 8, pp. 781–790. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © Yu.F. Kopnichev, I.N. Sokolova, 2017, published in Geofizicheskie Protsessy i Biosfera, 2017, Vol. 16, No. 1, pp. 42–54.

Ring-Shaped Seismicity Structures in Southern California: Possible Preparation for Large Earthquake in the Los Angeles Basin

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Abstract—Some characteristics of seismicity in Southern California are studied. It is found that ring-shaped seismicity structures with threshold magnitudes $M_{\rm th}$ of 4.1, 4.1, and 3.8 formed prior to three large ($M_w > 7.0$) earthquakes in 1992, 1999, and 2010, respectively. The sizes of these structures are several times smaller than for intracontinental strike-slip events with similar magnitudes. Two ring-shaped structures are identified in areas east of the city of Los Angeles, where relatively large earthquakes have not occurred for at least 150 years. The magnitudes of large events which can occur in the areas of these structures are estimated on the basis of the previously obtained correlation dependence of ring sizes on magnitudes of the strike-slip earthquakes. Large events with magnitudes of $M_w = 6.9 \pm 0.2$ and $M_w = 8.6 \pm 0.2$ can occur in the area to the east of the city of Los Angeles and in the rupture zone of the 1857 great Fort Tejon earthquake, respectively. We believe that ring-structure formation, similarly to the other regions, is connected with deep-seated fluid migration.

Keywords: Earth's crust, ring-shaped seismicity structures, large earthquakes, deep-seated fluids

DOI: 10.1134/S0001433817080072

INTRODUCTION

It was found in recent years that ring-shaped seismicity structures (seismicity rings) form around zones or relative seismic quiescence for several decades before many large earthquakes (Kopnichev and Sokolova, 2009a, 2009b, 2010, 2011a, 2011b, 2012, 2013a, 2013b, 2015). These structures are composed of the epicenters of events with magnitudes $M \geq M_{\rm th}$, where $M_{\rm th}$ is the threshold magnitude, whose value increases with the increase in energy of the mainshock. For a number of subduction zones, correlation dependences were obtained, namely, $L(M_w)$ and $M_{\rm th}(M_w)$, where L is the length of major axis of a seismicity ring and M_w is the magnitude of the respective large earthquakes (Kopnichev and Sokolova, 2009b, 2011a, 2013b). Analogous dependences were also obtained for large earthquakes with different focal mechanisms occurring in intracontinental regions (Kopnichev and Sokolova, 2011b, 2013a). Using these dependences, we can predict the locations and energies of preparing large earthquakes from characteristics of ring-shaped structures (Kopnichev and Sokolova, 2011a, 2011b, 2012, 2013b, 2015). The present article deals with such a prediction for Southern California.

BRIEF GEOLOGICAL–GEOPHYSICAL CHARACTERISTICS OF THE STUDY AREA

The tectonics of the region under study is determined by the Pacific Plate's northward motion past the North American Plate at an average rate of ~38 mm/yr (Powell and Weldon, 1992). The plate slips along the largest lateral strike-slip fault on Earth, the San Andreas Fault (Fig. 1). This fault is the location of the so-called Fort Tejon large ($M_w = 7.9$) earthquake that occurred in Southern California in 1857 (Fig. 1, Table 1). The name of this event is related to the locality where the severest damage was reported; the surface-rupture length was about 350 km and the maximal offset along it was about 9 m (Sieh, 1978). Paleoseismological data showed that these events occurred regularly in southern California for approximately 3000 years (Scharer et al., 2010). More than 150 years have passed after that event of 1857, and this is longer than the average recurrence interval for such earthquakes in the region; in this respect, some authors suppose that a new earthquake with $M \sim 8.0$ will occur here in the nearest future (Scharer et al., 2010). Additionally, four earthquakes with $M_w = 7.1$–7.5 have been recorded beginning from 1900: in 1952, 1992, 1999, and 2010. Note that the absolute majority of Californian earthquakes occur at shallow depths (down to 15 km) (Richards-Dinger and Shearer, 2000).

DATA AND METHODS

We used catalogs from the NEIC (National Earthquake Information Center) of the USGS (United States Geological Survey) containing data starting from 1945. The technique of distinguishing ring-

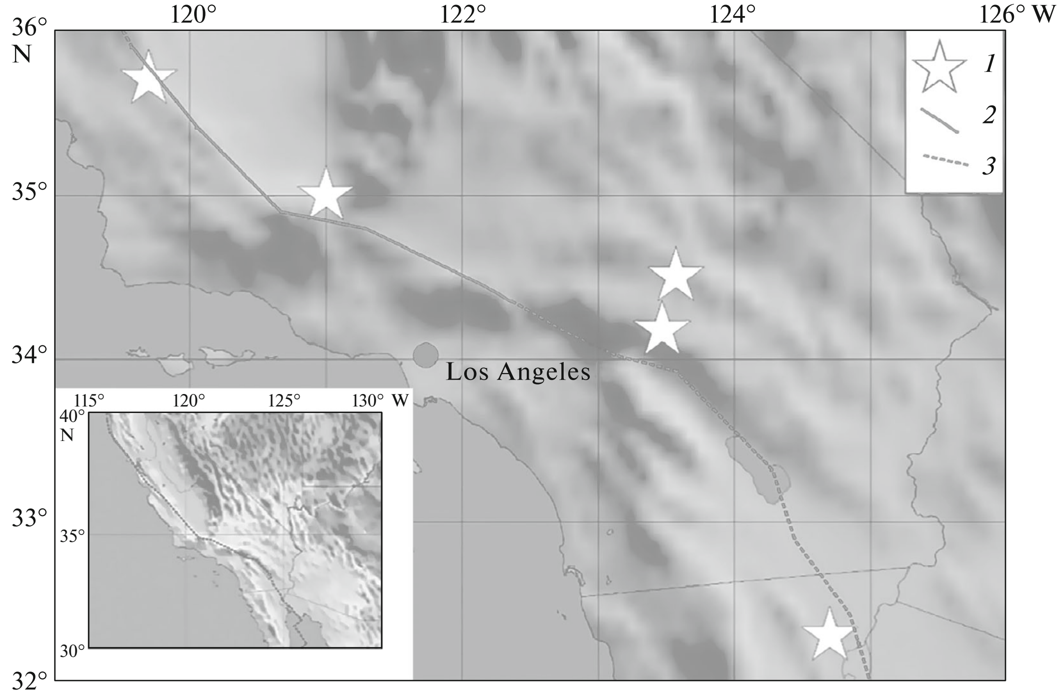

Fig. 1. Map of the study area: (*1*) epicenters of earthquakes with $M \geq 7.0$ beginning from 1850, (*2*) rupture formed after the earthquake of 1857, and (*3*) segment of the San Andreas Fault. Inset: the entire San Andreas Fault.

shaped seismicity structures in most continental regions includes the following.

(1) The duration of the period for which the characteristics of seismicity are studied varies depending on the study area; in the absolute majority of cases, it does not exceed 60 years (usually no more than 40 years).

(2) In the region under study, parameters of seismicity are analyzed in the range of depths from 0 to 33 km, where ring-shaped structures can form. The chosen events have magnitudes at least equal to the threshold one (M_{th}), and this value are usually 2–3 units lower than the mainshock magnitude.

(3) We adjust the values of threshold magnitudes M_{th} in order to find the optimal values at which ring-shaped structures are distinguished the most clearly.

(4) Ring-shaped structures are usually approximate by ellipses. Seismicity rings are constructed in a way that approximately an equal number of relatively weak events are located on both sides of the contours of ellipses. The seismicity ring is considered formed if the maximal width of the band of epicenters that form it (the sum of maximal deviations of epicenters located within and beyond the ellipse, relative to its contour) does not exceed 1/4 of the minor ellipse axis length (the criterion of the ring structure quality).

(5) A ring-shaped structure having the largest possible value of M_{th} is selected. All other things equal, the selected seismicity ring has the longest major axis of ellipse.

(6) The parameters of seismicity need to be controlled on a regular basis (at least once every half a year), because there have been cases reported when new ring structures with much greater M_{th} formed in 1–2 years; for example, this occurred before the Tohoku earthquake of March 11, 2011 (Kopnichev and Sokolova, 2011a).

Table 1. Large earthquakes in Southern California

Date (dd.mm.yyyy)	Coordinates, deg		M_w	h, km
	N	W		
09.01.1857	35.7	120.3	7.9	<10
21.07.1952	35.00	119.00	7.5	
28.06.1992	34.18	116.53	7.3	11
16.10.1999	34.51	116.43	7.2	5
04.04.2010	32.29	115.30	7.2	10

ANALYSIS OF DATA

On June 28, 1992, a large earthquake occurred in Southern California south of the San Andreas Fault (Landers, $M_w = 7.3$). The focal mechanism of this event was an oblique strike-slip (with a small component of normal faulting). Figure 2a shows the characteristics of seismicity in the vicinity of the source zone in the period from January 1, 1964, to June 27, 1992. We can see that a NW-elongated ring-shaped seismic-

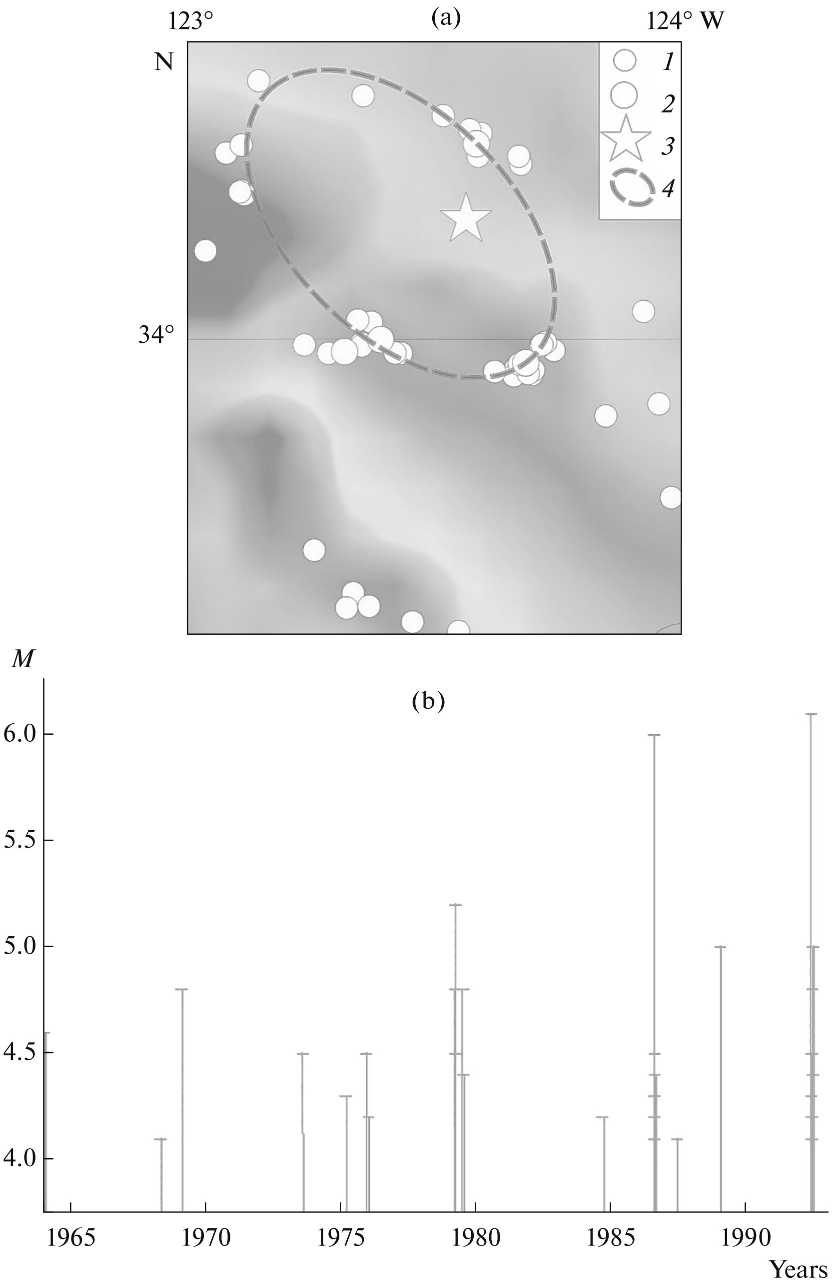

Fig. 2. Elements of seismicity before the Landers earthquake of June 28, 1992 (a), and dependence $M(T)$ for the ring-shaped structure (b). (*1*) Epicenters of earthquakes with $M = 4.1–4.9$, (*2*) $5.0 \leq M < 7.0$, and (*3*) mainshock; (*4*) seismicity ring.

ity structure formed before the Landers earthquake of June 28, 1992 ($M_{th} = 4.1$, $L \sim 70$ km). This structure formed in 1968–1992, and its largest ($M = 6.1$) earthquake in the ring zone occurred in 1992 (see Fig. 2b). The most remarkable feature is an abrupt growth of seismotectonic deformations (STDs rate) in 1986–1992. The epicenter of the Landers earthquake was located within the ring-shaped structure, near its eastern boundary.

To the north of the source of this earthquake, another large earthquake, known as Hector Mine, with $M_w = 7.1$, occurred October 16, 1999. The focal mechanism of this earthquake was almost pure strike slip. In the map shown in Fig. 3a, we can see that a narrow ENE-oriented ring-shaped seismicity structure ($M_{th} = 4.1$, $L \sim 55$ km) formed before this earthquake. It follows from what is shown in Fig. 3b that this structure formed in 1973–1996, and the largest ($M = 5.4$) earthquake in its zone occurred in 1992. In this case, the abrupt increase in STD rate was observed in 1992–1996. The epicenter of the Hector Mine earthquake was located at the eastern margin of the ring-

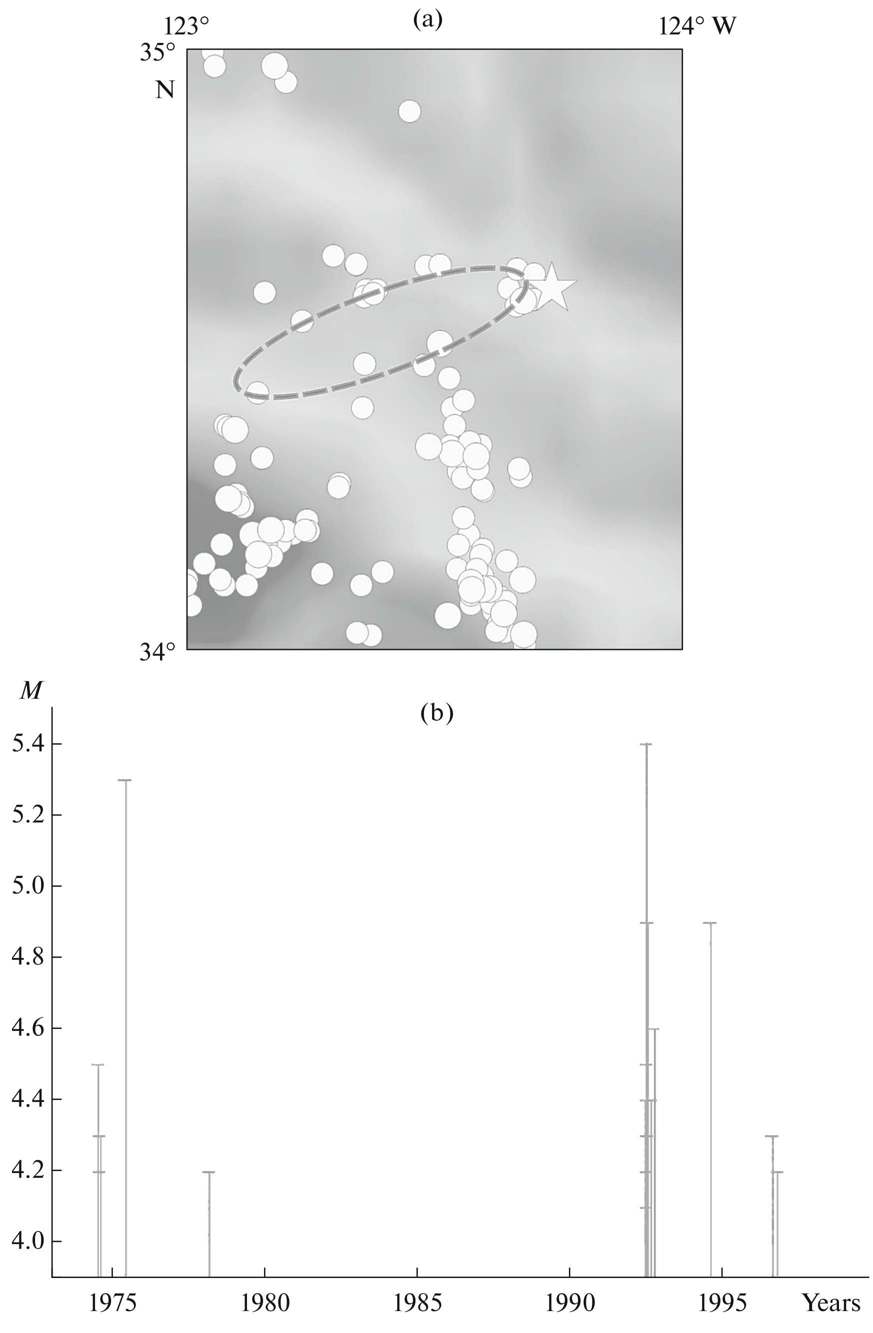

Fig. 3. Elements of seismicity before the Hector Mine earthquake of October 16, 1999 (a), and dependence $M(T)$ for the ring-shaped structure (b). Designations are same as Fig. 2a.

shaped structure. Interestingly, both considered seismicity rings touch each other at latitude of ~34.4° N.

On April 4, 2010, the Easter earthquake with M_w = 7.2 occurred in Southern California. The source of this event was hosted on the Laguna Salada active fault, and the focal mechanism was almost pure strike-slip. Figure 4a demonstrates the characteristics of seismicity in the source zone and its vicinity. It can be seen that a NW-elongated seismicity ring (M_{th} = 3.8, L ~ 55 km) manifested before the Easter earthquake. It follows from the data presented in Fig. 4b that this structure formed in 1974–2010, and the largest (M = 6.4) earthquake in its zone occurred in 1979. The dependence of earthquake magnitudes on time in the zone of ring-shaped structure is U-shaped, with the highest STD rated being reported in 1979–1980 and 2008–2010. The epicenter of the Easter earthquake was located about 10 km south of the seismicity ring.

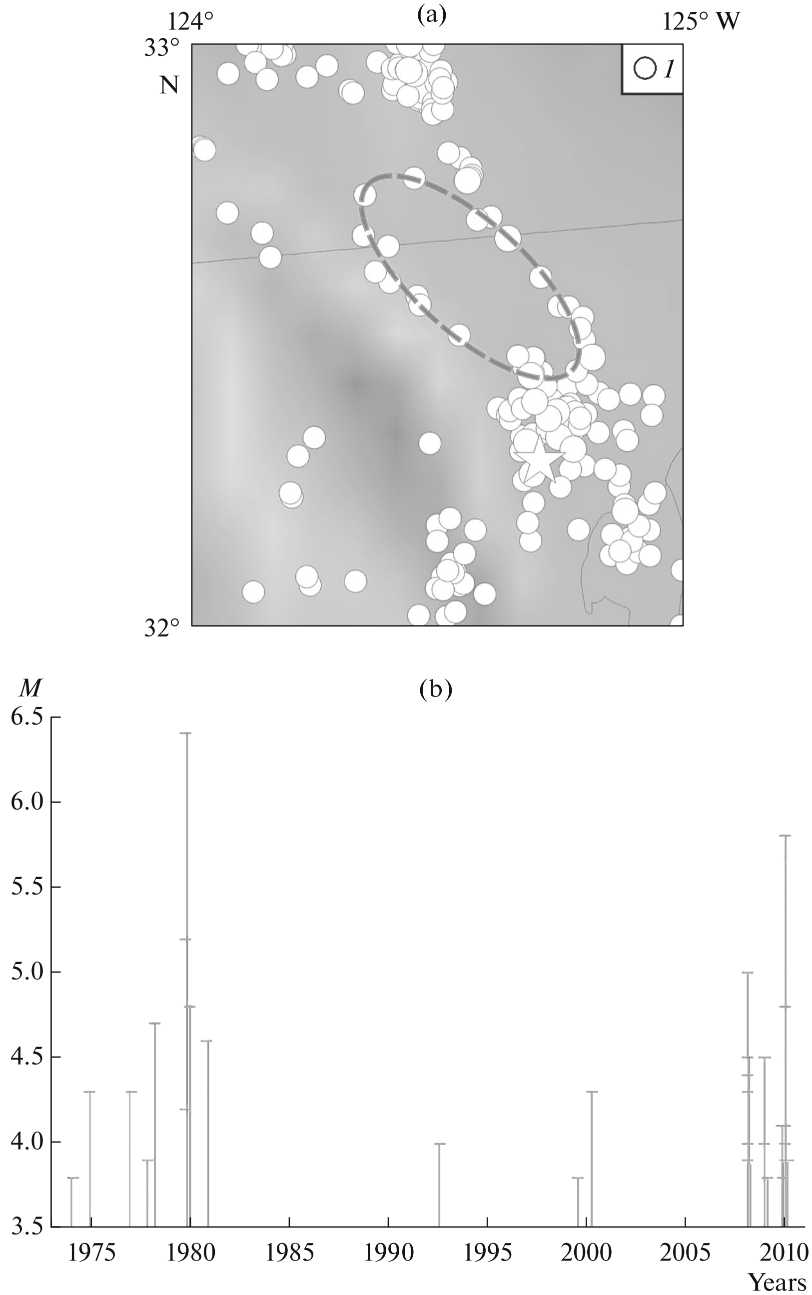

Fig. 4. Elements of seismicity before the earthquake of April 4, 2010 (a), and dependence $M(T)$ for the ring-shaped structure (b). (*1*) Epicenters of earthquakes with $M = 3.8–4.9$. The rest of the designations are the same as Fig. 2a.

Now let us consider the characteristics of seismicity in the areas where relatively large ($M \geq 7.0$) earthquakes have not been recorded for a long time. Figure 5a shows the epicenters of earthquakes with $M \geq 4.7$ in the area east of Los Angeles since 1973. It follows from this figure that a small ring-shaped structure formed here with a NW-oriented major axis ($L \sim 45$ km). This structure formed in 1987–2014 (Fig. 5b), and the highest magnitude in this zone ($M = 5.9$) was reported in 1987. After the period of relative quiescence in 1991–2007, seismic activation was observed in 2008–2014.

Figure 6a illustrates the characteristics of seismicity in the region confined by coordinates 33–36° N and 115–120° W beginning from 1945. In this case, a large sublatitudinally elongated ring-shaped structure manifested ($M_{th} = 5.5$, $L \sim 250$ km). The segment of the San Andreas Fault where the large earthquake of 1857 occurred crosses this structure. At the boundary of this seismicity ring, there are epicenters of large ($M > 7.0$) earthquakes of 1952, 1992, and 1999. This ring-shaped structure formed in 1947–1999 (Fig. 6b).

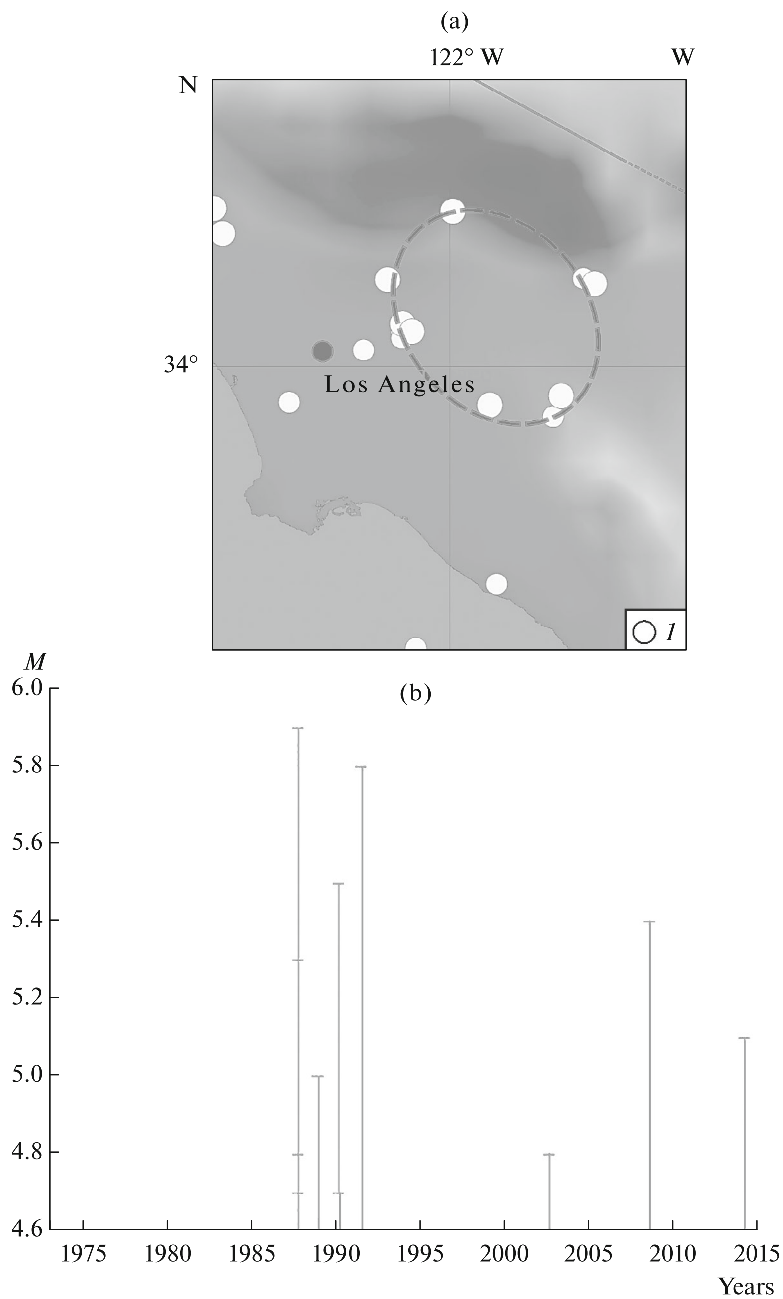

Fig. 5. Elements of seismicity in the area of the city of Los Angeles from January 1, 1973, to May 1, 2016 (a), and dependence $M(T)$ for the ring-shaped structure (b). (*1*) Epicenters of earthquakes with $M = 4.7–4.9$. The rest of the designations are the same as Fig. 2a.

Interestingly, two seismicity rings presented in Figs. 5a and 6a nearly touch each other at longitude of ~122° W.

ESTIMATION OF MAGNITUDES OF EARTHQUAKES CORRESPONDING TO RING-SHAPED STRUCTURES IN SOUTHERN CALIFORNIA

In (Kopnichev and Sokolova, 2013a), the correlation dependences were obtained linking magnitudes of large earthquakes with different focal mechanisms of earthquakes occurring in intracontinental regions, on the one hand, and sizes of ring-shaped structures that formed prior to these events. For earthquakes with strike-slip mechanisms, the following dependence was obtained (Fig. 7):

$$\log L\ (\text{km}) = -1.12 + 0.49M_w,\ r = 0.94, \qquad (1)$$

where r is the correlation coefficient.

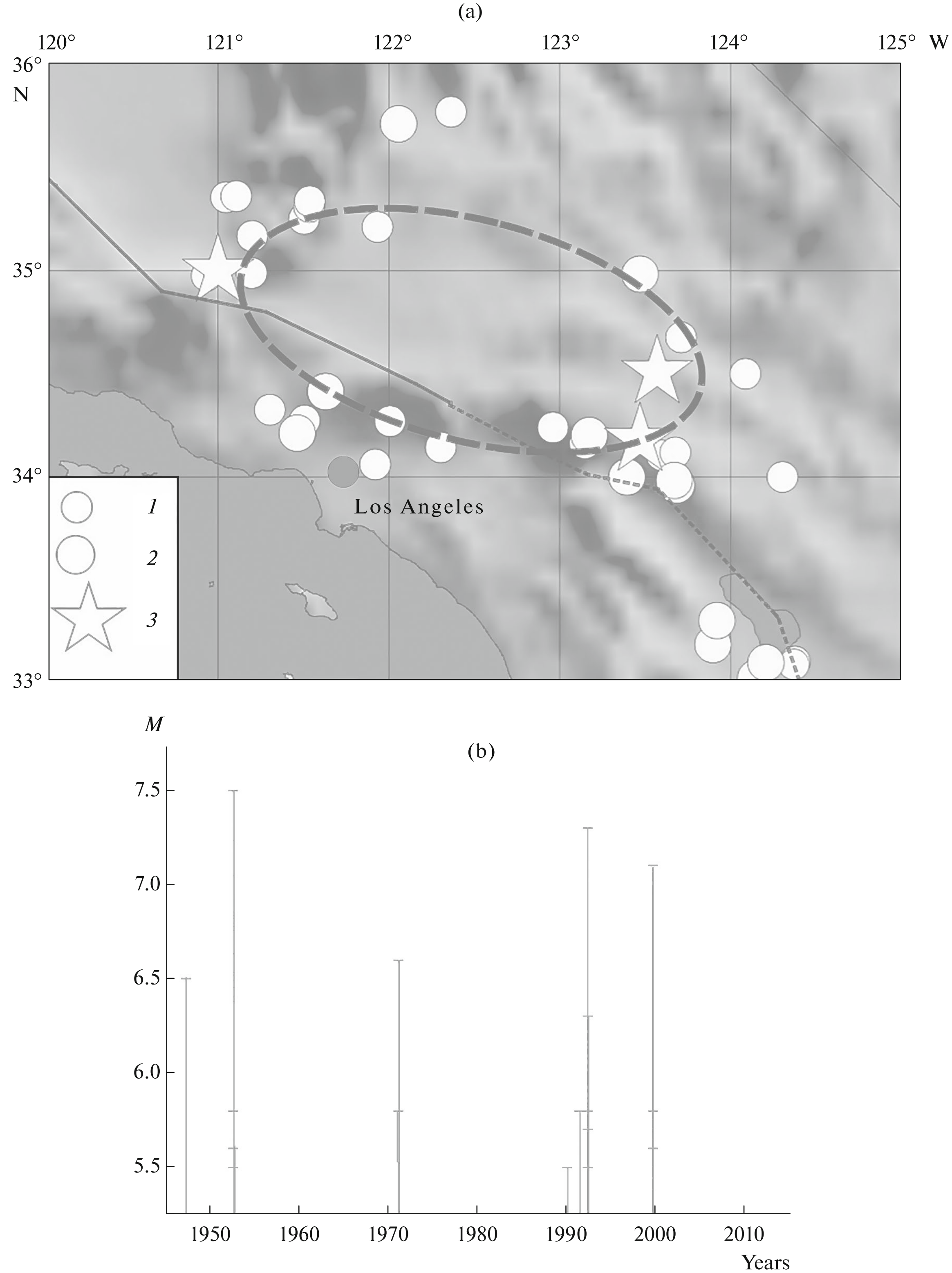

Fig. 6. Elements of seismicity in the region of Southern California from January 1, 1945, to May 1, 2016 (a), and dependence $M(T)$ for the ring-shaped structure (b). Epicenters of earthquakes with (*1*) $M = 5.5–5.9$, (*2*) $6.0 \leq M < 7.0$, and (*3*) $M \geq 7.0$. The rest of the designations are the same as Figs. 1 and 2a.

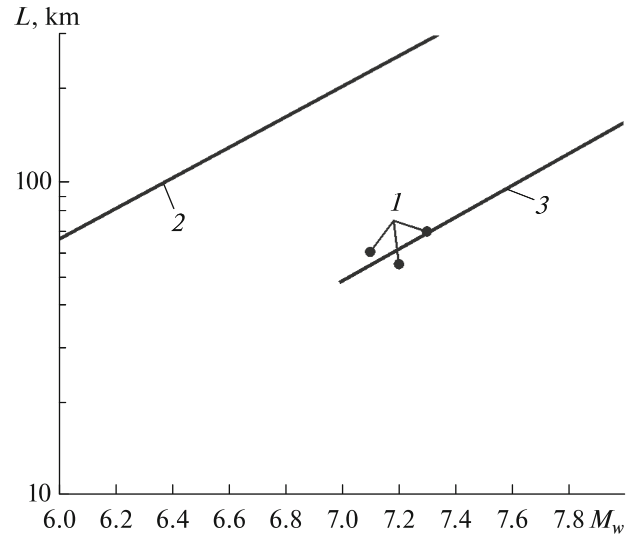

Fig. 7. Values of $L(M_w)$ for three ring-shaped structures in Southern California (*1*) relative to correlation dependence (*1*), obtained for intracontinental regions (*2*), and the analogous dependence for the region of Sumatra (*3*).

This dependence has a quite high value of *r*; therefore, we used it as first approximation estimates of large earthquakes that may occur in the zones of identified ring-shaped structures. It follows from Fig. 7 that values L in Southern California are significantly underestimated for the given magnitude M_w compared to average values obtained for intracontinental regions. Interestingly, the data for three ring-shaped structures considered above are close to the correlation dependence found for the region of Sumatra (Kopnichev and Sokolova, 2013a, 2009b). In this respect, we supposed that the slope of the $\log L(M_w)$ graph for the region of Southern California corresponds to dependence (1), and the level of the graph is shifted relative to it by C = const:

$$\log L\ (\text{km}) = -1.12 + C + 0.49M_w. \qquad (2)$$

By using the data obtained for three events (Figs. 2–4), we find the average value of $C = -0.66 \pm 0.11$. We estimated average values M_w, which may correspond to ring-shaped structures presented in Figs. 5a and 6a, by formula (2) at the given value of C. It follows from the data in Table 2 that an event with $M_w = 6.9 \pm 0.2$ may be under preparation in the zone of the smaller ring and one with $M_w = 8.6 \pm 0.2$ in the area of the larger ring. Of course, these values should be considered as first approximation estimates.

Table 2. Parameters of ring-shaped structures in zones of the possible preparation of large earthquakes in Southern California

Coordinates, deg		L, km	M_{th}	M_w (predicted)
N	W			
33.5–34.5	117.5–118.5	45	4.7	6.9 ± 0.2
34.0–35.5	115.5–119.5	280	5.5	8.6 ± 0.2

DISCUSSION

The data obtained in previous sections indicate that the region of Southern California, as well as many other intracontinental regions (Kopnichev and Sokolova, 2010, 2012, 2013a) and subduction zones (Kopnichev and Sokolova, 2009a, 2009b, 2010, 2011a, 2011b, 2013b, 2015), is characterized by the formation of ring-shaped seismicity structures before most large earthquakes. It was noticed in (Kopnichev and Sokolova, 2010, 2011a, 2011b, 2012, 2013a, 2013b, 2015) that the formation of ring-shaped seismicity structures is related to processes of self-organization in geological systems (Letnikov, 1992), which are manifested in the migration of deep-seated fluids in the Earth's crust and upper mantle. These processes eventually lead to a decrease in potential energy of the planet.

Migration of fluids is implemented in various ways, depending on their content in rocks and on rock permeability. At the initial stage, fluids are in the form of isolated drops clustered in corners of rock grains (Rodkin, 1993). Under the effect of shear stresses, fluids begin to slowly form the linking network by aligning along faces of grains (Hier-Majumder and Kohlstedt, 2006). At the top of the two-phase layer, where it contacts the linking network of fluids filling the pores and cracks, the difference between densities of a fluid and host rock causes the concentration of stresses (Gold and Soter, 1984/1985). If the thickness of this layer is sufficient, the hydraulic fracture of the top takes place and a certain part of fluids ascends upwards relatively rapidly, and this process can multiply repeat (Gold and Soter, 1984/1985). Most likely, earthquakes are one of the main mechanisms providing the rapid upward migration of fluids (Sibson et al., 1975).

It was hypothesized in (Kopnichev and Sokolova, 2013b) that energy of large earthquakes in interplate zones is proportional to potential energy of fluids, which is released during the preparation and occurrence of these events. Accepting this hypothesis, we can explain, in particular, very low values of L for ring-shaped structures formed in subduction zones when compared to intracontinental regions (Kopnichev and Sokolova, 2009a, 2009b, 2010, 2011a, 2011b, 2012, 2013a, 2013b, 2015). We can attribute this effect to the relatively low fluid content in the continental lithosphere (*Glubinnoe...*, 1987). The data presented above indicate that values of L are also significantly underestimated in the case of Southern California. This may be an indication of a quite high fluid content, at least in the crust of the region under study. However, the absence of relatively deep-focus earthquakes can indicate low fluid content in the upper mantle. To verify these suggestions, we plan to investigate the characteristics of attenuation field of short-period *S*-waves in the crust and upper mantle of California.

It should be noted that the intensive migration of deep-seated fluids in the zone of the San Andreas Fault and its vicinity is also indicated by the data on high values of the $^3He/^4He$ isotope ratio from hydrothermal waters (Kennedy et al., 1997), which is evidence for the uplift of mantle helium into the upper crust.

Of special interest are the data on ring-shaped structures in zones where no large earthquakes have been being reported for quite a long time. It follows from the estimates given above that an earthquake with $M_w \sim 7$ is possibly prepared in the area located east of the city of Los Angeles, while that with $M_w \sim 8.5$ is prepared in the zone of the San Andreas Fault. Both earthquakes can cause human deaths and considerable destruction in densely populated areas with developed industries. Note that the increase in STD rate is often observed in the areas of ring-shaped structures several years before large and great earthquakes with which the formation of the mentioned structures is associated (Kopnichev and Sokolova, 2010, 2011a, 2011b, 2012, 2013a, 2013b, 2015) (it is also seen in Figs. 2–4). However, no earthquakes with $M \geq 5.5$ were recorded in the area of the larger seismicity ring after 1999. In this respect, we suppose that the most probable location of the large earthquake is the zone of smaller seismicity ring, east of Los Angeles, where two earthquakes with $M > 5.0$ occurred in 2008–2014. In our opinion, geophysical and geochemical studies should be launched in this region for the purpose of a possible midterm prediction of a large seismic event.

CONCLUSIONS

We have considered some characteristics of seismicity in Southern California (the region between 32° and 36° N) by using a technique based on distinguishing ring-shaped seismicity structures. It has been found that ring-shaped seismicity structures with threshold magnitudes M_{th} of 4.1, 4.1, and 3.8 formed over several decades prior to three large ($M > 7.0$) earthquakes in 1992, 1999, and 2010, respectively. Importantly, the sizes of these structures are several times less than for intracontinental strike-slip events with the similar magnitudes. Two ring-shaped structures (smaller and larger) have been identified in the areas to the east of the city of Los Angeles, where relatively large earthquakes have not been occurring for at least 150 years. The smaller and larger structures began to form in 1987 and 1947, respectively. Based on the earlier obtained correlation dependence of the seismicity ring size on the mainshock magnitude for intracontinental strike-slip earthquakes, we have estimated magnitudes of the large earthquakes that may occur in the areas of these ring-shaped structures: $M_w = 6.9 \pm 0.2$ in the area east of the city of Los Angeles and $M_w = 8.6 \pm 0.2$ in the area where the large earthquake occurred in 1857. We suppose that the formation of ring-shaped structures is related to the processes of self-organization in geological systems; resulting from these processes, deep-seated fluids migrate upwards, eventually leading to a decrease in potential energy of the Earth. The data obtained in the present work, as well as those from earlier ones, indicate the promising applicability of the technique for predicting locations and magnitudes of large earthquakes in different regions of the world.

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Translated by N. Astafiev